

Received: 6 January 2025 • Revised: 02 March 2025 • Accepted: 25 March 2025

Research

doi: 10.22034/jcema.2025.539472.1162

Testing and Specifying Electrochemical Properties of Expanded Shale, Clay and Slate Lightweight Aggregates

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ABSTRACT

Electrochemical properties of earthen materials, including lightweight aggregates can be useful to assess the corrosivity and performance of metallic materials embedded within backfills. Electrical conductivity, the reciprocal of resistivity, relates to the transport of electrons during the corrosion process. Other chemical properties such as pH and ion contents interact with physical conditions like moisture content and gradation to influence the electrical conductivity. Sulfate and chloride contents are major performance measures in laboratory testing methods. These predictors are perceived as more accessible performance measures, but not necessarily more accurate, than direct assessment of corrosion like mass loss or instantaneous measures of corrosion potentials and corrosion using electrochemical measurement techniques. However, these measures do not address the full spectrum of material characteristics influencing corrosivity. This shortcoming is apparent for lightweight aggregates that exhibit different trends with respect to electrochemical properties compared to normal weight aggregates due to their characteristic porosity and moisture dynamics. Hence, application of ESCS lightweight aggregates requires modification of testing methods and specification of alternative thresholds for electrochemical properties, including electrical resistivity, pH, sulfate and chloride ion contents. This paper addresses such modifications using the outcomes of experimental investigations.

Keywords: lightweight aggregates; corrosion rate; mechanically stabilized earth;

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1. INTRODUCTION

1.1. Corrosion Potential of Geomaterials

Several electrochemical parameters, such as electrical resistivity, degree of saturation, pH, and dissolved salts influence the corrosivity of earthen materials [1]. Most salts promote corrosion, except for carbonate, which forms a protective scale on metals. Chloride, sulfate, and sulfide are major promoters of corrosion in steel reinforcements. Resistivity is a significant indicator of corrosivity. Key factors affecting corrosion include temperature,

oxygen concentration, resistivity, pH, carbonate scaling tendency, acids, alkalis, salts, soil particle size distribution, porosity, water content, and microbial activity [2],[3].

1.2. Electrical Conductivity/Resistivity

This is a primary indicator of corrosion potential. High electrical conductivity (low resistivity) facilitates electron transport, accelerating corrosion.

Conversely, low conductivity (high resistivity) is correlated with low corrosion rates [4].

1.3. pH Levels

The acidity or alkalinity of the soil affects corrosion rates. Highly acidic (low pH) or highly alkaline (high pH) environments can increase corrosion rates. Neutral pH levels are generally less corrosive. The pH of ESCS ranges between approximately 8 and 9.5 [2].

1.4. Corrosive Ions

The presence of ions like chlorides and sulfates significantly impacts corrosion. Chlorides, for example, can break down protective oxide layers on metals, leading to accelerated corrosion. Sulfates can also contribute to corrosion, especially in the presence of moisture.

1.5. Moisture Content

Water acts as an electrolyte, facilitating the movement of ions and electrons, which is essential for the corrosion process. The highest corrosion rates are generally associated with the degree of saturation between 65% and 90%. If the soil is saturated, the resistivity may be the lowest, but the lack of oxygen leads to lower corrosion rates.

1.6. Soil Composition and Gradation

The physical characteristics of the soil, including particle size distribution and porosity, affect its moisture retention and drainage properties, which in turn influence corrosivity.

2. Description and Characteristics of ESCS LWA

This report emphasizes the use of rotary-kiln-manufactured expanded shale, clay and slate (ESCS) lightweight aggregates. **Figure 1** exhibits the simplified and schematic production process that is largely uniform worldwide, with differences in aggregate properties stemming from the raw materials used—shale, clay, or slate (**Figure 2**). Consequently, the physical and mechanical properties of these manufactured aggregates show less variation compared to those from mines, recycled sources, or industrial byproducts, which lack the quality control processes of a manufacturing plant [5].

The visual attributes of rotary-kiln-manufactured lightweight aggregates, including color, shape, and size, can vary depending on the source, as illustrated in **Figure 2**. Post-production screening processes

1.7. Temperature

Higher temperatures can increase the rate of chemical reactions, including those involved in corrosion. Thus, warmer environments can lead to higher corrosion rates.

1.8. Organic Content

Organic materials in the soil can produce acids as they decompose, which can increase the soil's corrosiveness. The presence of organics also contributes to the respiratory processes of microorganisms that can influence corrosion.

1.9. Presence of Microorganisms

Certain bacteria can influence corrosion processes, either by producing corrosive substances or by directly interacting with the metal surfaces.

1.10. Type of Aggregate

Lightweight aggregates, such as ESCS (Expanded Shale, Clay, and Slate), have different electrochemical properties compared to normal weight aggregates due to their higher porosity and unique moisture dynamics. This necessitates modified testing methods and alternative thresholds for assessing corrosion potential [2].

Understanding these factors helps in selecting appropriate materials and designing effective corrosion protection strategies for infrastructure projects. The major shortcoming in current practice has roots in the standard approaches to the measurement of these factors, which is the primary contribution of this paper.

allow for customization of these aggregates to meet specific application needs. Despite these visual differences, the physical and mechanical properties—such as porosity, absorption, density, and strength—remain consistent. This uniformity is due to the identical chemistry of vitrified aggregates and the porous microstructure created in the rotary kiln, ensuring similar properties across products from different manufacturers located within the North America (**Figure 3**) or worldwide [6].

The use of alternative materials like lightweight ESCSs in North America, Europe, and Asia has become increasingly popular due to their light weight, ease of compaction, sustainability, and durability ([7]-[9]). ESCSs improve drainage and reduce corrosion compared to on-site materials. Experimental shake table studies on lightweight

backfills have shown that low density, a high internal friction angle, and high damping are crucial for the high performance of MSE systems ([10]-[14]).



Figure 1. Sample aggregates stored in sealed containers to preserve the as-received condition before testing.



Figure 2. Sample Expanded Shale with Coarse, Medium, and Fine Gradations (from left to right)



Figure 3. ESCSI Production Plants (Courtesy of ESCSI)

3. Sulfate and Chloride Measurements

3.1. Range of measurements for ESCS LWA

Sulfate and chloride measurements for Expanded Shale, Clay, and Slate (ESCS) lightweight aggregates are typically conducted to assess the durability and stability of these materials in various applications. The testing methodology influences the results through sample preparations. ESCS aggregates typically have low chloride contents, 10 to 70 ppm, and magnesium sulfate soundness loss, less than 6%, compared to 100 ppm and 30% commonly specified limits, respectively [15]. Regardless, it is not uncommon for ESCS aggregates to exhibit high sulfate contents compared to most normal weight

aggregates. However, these high values may not necessarily lead to high corrosion rates.

3.2. Specified limits for MSE wall fill

Most transportation agencies assess the electrochemical properties of earthen materials using AASHTO laboratory test standards established in the early 1990s. The specified methods include AASHTO T 288 for resistivity, AASHTO T 289 for pH, AASHTO T 290 for soluble sulfate content, and AASHTO T 291 for soluble chloride content. AASHTO outlines the electrochemical criteria for fill materials suitable for MSE wall construction, as detailed in **Table 1** [3].

Table 1. AASHTO Requirements for MSE Wall Backfills [3]

Parameter	Acceptable Range	AASHTO Standard
Minimum Resistivity ($\Omega\cdot\text{cm}$)	3000	T 288
pH range	5-10	T 289
Maximum Sulfate Content (ppm)	200	T 290
Maximum Chloride Content (ppm)	100	T 291
Notes: $\Omega\cdot\text{cm}$: ohm-centimeter; ppm: parts per million		

4. Objectives of the Paper

This paper evaluates test methods and specification of electrochemical properties of expanded shale, clay and slate (ESCS) lightweight aggregates. The primary objective of the paper is to analyze and compare data from laboratory and field studies to determine characteristics of ESCS related to corrosivity.

4.1. Demonstrate sulfate and chloride measurements are not properly measured for ESCS LWA

AASHTO T 288, T 289, T 290, and T 291 are conducted on specimens separated using a No. 10 sieve. For coarse fills with minimal or no material passing through the No. 10 sieve, obtaining enough fines for testing may require sieving a large quantity of material. This approach is impractical and can lead to inaccurate results, especially for gravel fills with very little fine material. Crushing larger aggregates to obtain finer fractions is neither appropriate nor permitted by AASHTO standards, unless breakage is expected during placement and compaction. This is because most soluble ions are concentrated on particle surfaces, with negligible diffusion through the particles. Testing the finer portion (passing the No. 10 sieve, finer than 2.00 mm) assumes these fractions are significant sources of soluble salts, which may not be true for coarse fills with little or no fine material. In such cases, an alternative testing method should be considered [3].

4.2. Not consistent with measurements of other electrochemical properties

Sulfate and chloride ion contents facilitate electron movements during the corrosion process and hence, influence electrical conductivity. These indicators often synergize with other indicators such as pH to affect the corrosion rate of embedded metals in backfills [2].

4.3. Not useful for characterizing corrosivity in coarse backfills

Existing standards such as AASHTO T 290 and T 291 address measurements of water-soluble sulfate and chloride ion contents for fine soil particles, that is passing 2-mm (#10) sieve [16]. Thus, determining these ions in coarse backfills require modification of testing methods. In response to this need, local agencies like Texas DOT have considered revised standards to measure sulfate and chloride ion contents in coarse backfills ([17]-[21]).

4.4. Effect of Moisture Content

Darbin, Jailloux, and Montuelle (1988) observed that the highest corrosion rates occur at moisture saturation levels between 60% and 85% [22]. Elias et al. (2009) studied fourteen active sites in California and found that most backfills had saturation levels above 65% [23]. Therefore, it is essential to assess the impact of moisture levels in MSE wall backfill on the corrosion of embedded steel reinforcement. Soil moisture influences the properties of the soil-metal interface, electrical conductivity, and ionic migration in soils, all of which directly affect corrosion processes [24]. Consequently, corrosion of embedded metallic reinforcement is negligible under dry conditions. Research has suggested that there may be an optimal moisture level that maximizes the corrosion rate, depending on the interaction between electrical conductivity and oxygen diffusion [25]. Thus, the funicular state of moisture in soil causes more corrosion damage to ferrous materials than the pendular state. This is significant because fine soil particles, such as clay, tend to have higher saturation levels than coarser particles like silt or sand [26].

4.5. End point

Comparison of various measurement techniques reveal that sample preparation techniques influence the results. These techniques may include sample origin, sieving, water equilibration time and dilution rate, drying time and temperature, extraction time

and method, and clarifying method [27]. The applicability of results to material selection specifications depends on how well these techniques

5. Data from Sulfate and Resistivity Measurements

5.1. MTI Data (ESCS LWA) – Lab

Tests for resistivity and sulfate content include measurements on coarse and fine samples from different sources identified as LW1, LW2, LW3, LW4, LW5, LW6, LW7, LW8 and NWCx. The gradation of the coarse samples complies with common blends for geotechnical applications produced by each manufacturer that contributed samples for the MTI study [2]. Samples LW1, LW3, LW4, LW6, LW7, LW8 and NWCx include less than 10% of the particle sizes passing the No. 10 sieve. Samples LW2 and LW5 were blended aggregates with 50% to 60% particle sizes passing the No. 10 sieve and could be separated on the #10 sieve in preparation for testing in accordance with existing AASHTO standards. Samples LW1, LW3, LW4, LW6, LW7, LW8 and NWCx were tested according to Tex-620-M using the as-is gradations. For comparison purposes, a fine gradation was obtained

represent the actual conditions for a given application.

5.2. Sulfate - AASHTO T 290, Tex-620-M, Leachate from resistivity test box

Figure 4 presents results from sulfate content measurements on 8 sources of ESCS (LW1 through LW8) and 1 normal weight sample (NWCx). Details of the test procedures are described in MTI (2023). As-is gradations were tested in accordance with Tex-620-M, and the crushed samples and blended aggregates (LW2 and LW5) were separated on the #10 sieve and tested in accordance with AASHTO T 290. Additionally, tests were performed on leachate drained from the test box used for resistivity testing after soaking the aggregates for 24 hours (24-hr saturated).

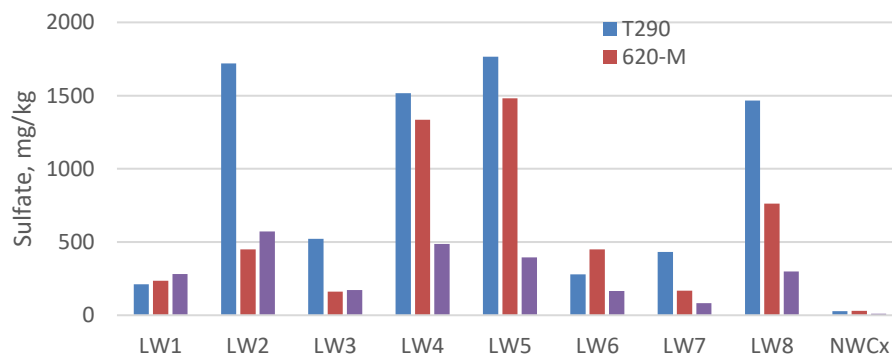


Figure 4. Comparison of sulfate contents of selected samples using different standards [2].

AASHTO T 290 describes two methods/techniques that may be used for measurements of sulfate content including gravimetric and turbidimetric methods. The different measurement techniques involve different sources of interference/error. For instance, employing gravimetric measurements, as opposed to the turbidimetric measurements applied by MTI (2023), makes a difference. These differences could be due to sources of interference such as the presence of sulfite or sulfide which have an effect on gravimetric measurements.

All of the sulfate contents measured from samples of ESCS were higher than those observed for the normal weight soil. In general, sulfate contents measured with the as-is gradations (Tex-620-M), are lower than

those measured on the finer fraction (i.e., passing the #10 sieve) via AASHTO T 290, indicating that finer gradations have higher sulfate contents compared to coarser ESCS samples.

Sulfate contents measured on the fine gradations of ESCS (AASHTO T 290) range between 200 ppm and 1750 ppm with 7 out of 8 samples higher than 200 ppm, and those measured from the as-is coarse gradations (Tex-620-M) are between 200 ppm and 1450 ppm with 5 out of the 8 samples higher than 200 ppm. Tests on samples of leachate from the resistivity test box after soaking for 24 hours are approximately equal to or lower than those measured with Tex-620-M, and these sulfate measurements range between

100 ppm and 600 ppm with half of the measurements (4 out of 8) higher than 200 ppm.

The comparison between results obtained with coarse or fine gradations is relatively close from sources LW1, LW4 and LW5. LW2 and LW5 are blended aggregates with nearly 55% passing the #10 sieve, such that measurements with the as-is gradation are controlled by the presence of the finer portion, but the same cannot be said for sources LW1 and LW4. However, the gradations for LWC1 and LWC4 are close to one another, and these samples have a higher sand content compared to the other coarse samples, which are mostly gravel size (> 10% sand, except for LWC8, with a gradation close to LWC4).

The sulfate contents measured with LW1 were the lowest ranging between 200 and 250 ppm, and the highest sulfate contents (approximately 1750 ppm) were observed from LW2 and LW5, both of which were blended aggregates with approximately 60% passing the No. 10 sieve.

5.3. Resistivity – AASHTO T 288, Tex-129-M

Table 2 presents resistivity measurements performed on samples of coarse and fine ESCS samples. Samples with fine gradations were tested in accordance with AASHTO T 288 and coarse samples tested via Tex-129-M. None of the coarse samples

have more than 5% of the particle sizes passing the No. 10 sieve such that the AASHTO T 288 test standard is not applicable (see Note 1 from AASHTO T 288). As described in NCHRP Report 958 [3], the modified Texas test standard Tex-129-M can be applied to measure the resistivity of coarse samples and is useful for characterization of corrosivity.

The following observations are made from the data presented in [Table 2](#) and resistivity measurements from samples of fine and coarse ESCS.

- Fine samples have low resistivity (between 1852 Ω -cm and 3848 Ω -cm) compared to the resistivity measurements from the coarse samples/as-is gradations (between 2343 Ω -cm and 43,244 Ω -cm).
- Measured resistivity for half of the fine samples (4 out of 8) are less than 2000 Ω -cm including measurements from samples LWF1, LWF2, LWF4, and LWF8.
- Resistivity > 3000 Ω -cm were measured from two of the fine samples including LWF6 and LWF7.
- Only one coarse sample, LWC4, had measured resistivity less than 3000 Ω -cm, and the resistivity measurement from LWC8 (3264 Ω -cm) is low compared to the other coarse samples with resistivity more than 15000 Ω -cm.

Table 2. Resistivity Measurements on Samples of ESCS/LWF (adapted from MTI, 2023)

Fine Samples	Resistivity AASHTO T 288 (Ω -cm)	Blended or Coarse Samples	Resistivity Tex-129-M (Ω -cm)
LWF1	1983	LWC1	16,133
LWF2	1852	Blended	2346
LWF3	2771	LWC3	29,050
LWF4	1882	LWC4	2715
LWF5	2646	Blended	3259
LWF6	3848	LWC6	30,385
LWF7	3553	LWC7	43,244
LWF8	1922	LWC8	3264
NWFx	9695	NWCx	24,812

5.4. Correlate sulfate and resistivity measurements

Figure 5 depicts the correlation between sulfate content and resistivity measurements from samples of fine (passing the No. 10 sieve) and coarse or blended samples. For the fine samples the sulfate content and resistivity were measured in accordance with AASHTO T 290 (sulfate) and T 288 (resistivity), and the coarse or blended samples were tested according to Tex-620-M (sulfate) and Tex-129-M (resistivity). These data indicate a general

trend whereby sulfate content and resistivity are negatively correlated, i.e. resistivity is lower at higher sulfate contents.

A good correlation between sulfate content and resistivity ($R^2 \approx 0.9$) is realized for the fine samples. Data points for blended and coarse samples with higher fines contents (e.g., LW2 and LW5) are close to the trend line of the fine samples, and those with negligible fines show substantially higher resistivity. This explains the lower coefficient of determination

($R^2 \approx 0.2$) for the trendline representing blended and coarse samples as opposed to the fine samples with particle sizes that pass the No. 10 sieve.

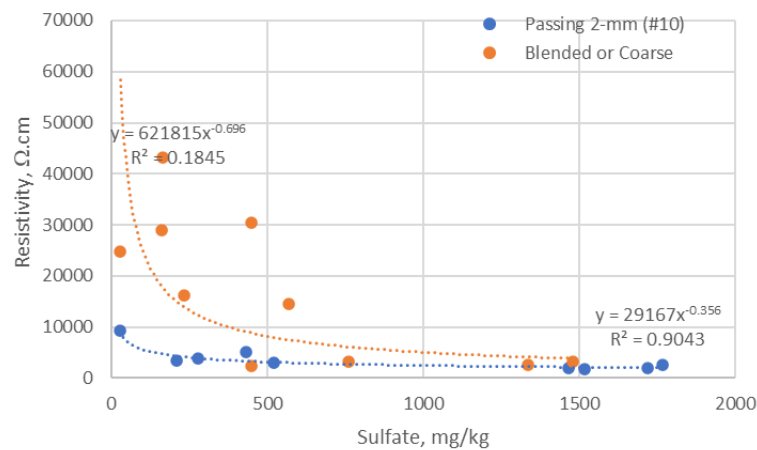


Figure 5. Electrical resistivity as a function of sulfate contents [2]

5.5. NCHRP Data (normal weight)

As described in NCHRP Report 958 [3], 24 samples of normal weight and 3 samples of lightweight (ESCS) fill were included in the test program for NCHRP Project 21-11. Samples came from various sources throughout North America including New York (5 sources), North Carolina (3), South Carolina (2), Florida (1), Louisiana (1), Arkansas (1), Texas (10), British Columbia (1), and Calgary (1). The mineralogy of aggregate sources includes limestone (13), granite (2), sandstone (1), natural sands/silica (6), glacial till (1) and expanded clay light weight fill (2).

The samples represent a broad range of gradations and compositions ranging from fine sand to coarse, clean, and open-graded, gravel. The composition is described in terms of the percentages of gravel (% retained on ¼ inch sieve), coarse to medium sand (passing ¼ inch and retained on the No. 40 sieve), fine sand (passing the No. 40 sieve and retained on the No. 200 sieve) and fines (% passing the No. 200 sieve). We summarize the composition of the materials as follows:

- Three samples were predominately (i.e., more than 50%) fine sand,
- Six samples were predominately coarse to medium sands,
- Two samples were mixtures of fine and coarse particles, where none of the components were equal to or greater than 50% of the total,

- Sixteen samples were predominately gravel varying from sandy gravels to clean and open graded gravels with no sand content, and
- None of the samples had more than 5% passing the No. 200 sieve.

5.6. Sulfate AASHTO T 290 and Tex-620-M

Figure 6 presents data from testing 9 samples with different gradations including one sample of lightweight fill (ESCS) collected from a site in South Carolina. Based on its gradation, the lightweight fill has the consistency of a medium to fine grained sand with approximately 65% passing the No. 10 sieve. Compared to the samples of ESCS tested by MTI (2023) this is considered as a fine LWF, similar to LWF2 and LWF5. The data in [Figure 6](#) are organized from left to right in terms of coarseness with the finest sample (Florida) on the left hand side and the coarsest sample (Wake Forest) on the right.

Sulfate contents measured on the ESCS LWF are the highest and equal to 700 ppm (not considering Tex-620-J) as measured by AASHTO T 290. Measurements via Tex-620-M are lower (425 ppm) but still above the 200 ppm threshold. Measurements of sulfate contents from the normal weight samples are less than or close to 200 ppm.

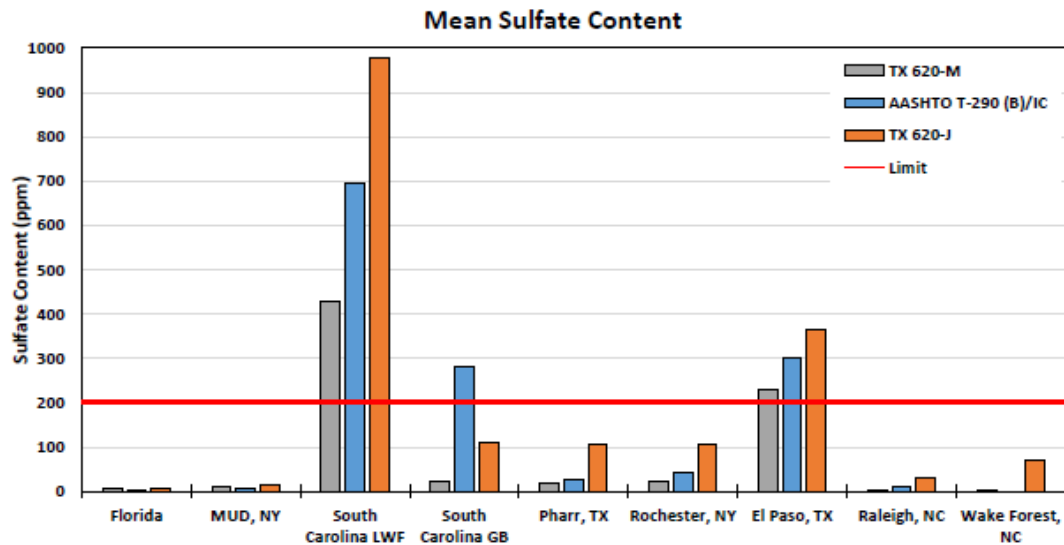


Figure 6. Sulfate Contents Measured from NCHRP Project 21-11 [3].

5.7. Resistivity – AASHTO T 288, Tex-129-M

During the course of the study for NCHRP Project 21-11, 5 different test standards or proposed test standards were considered for measurement of resistivity including AASHTO T 288, ASTM G187, Tex-129-E, Tex-129-M, and ASTM WK24621. These procedures differ in the particle sizes included in the test specimen, the preparations of the specimen before testing, the size of the test box (which depends on the maximum particle size), and the moisture content at which the minimum resistivity is recorded [3].

Figure 7 presents results from resistivity measurements performed on 9 different sources of materials including 1 source of ESCS (South Carolina LWF). Similar to the presentation of the sulfate measurements depicted in Figure 6, the data in Figure 7 are organized from left to right in terms of coarseness with the finest sample (Florida) on the

left hand side and the coarsest sample (Wake Forest) on the right. For materials consisting of finer gradations (e.g. Florida; MUD NY) the resistivity measured by the different test standards are similar, with all measurements within 10% of the average. For samples with coarse gradations (e.g., Raleigh, NC; Wake Forest, NC) substantial differences are observed between measurements made with AASHTO T 288 or Tex-129-M.

The measured resistivity of the ESCS is close to the 3000 Ω -cm threshold, which is lower compared to 6 out of 8 of the normal weight samples. This is expected given the high sulfate contents observed for the ESCS, but two of the sources including Rochester, NY and El Paso, Texas have lower measured resistivity. These sources had high chloride contents that affected the measured resistivity of these normal weight samples.

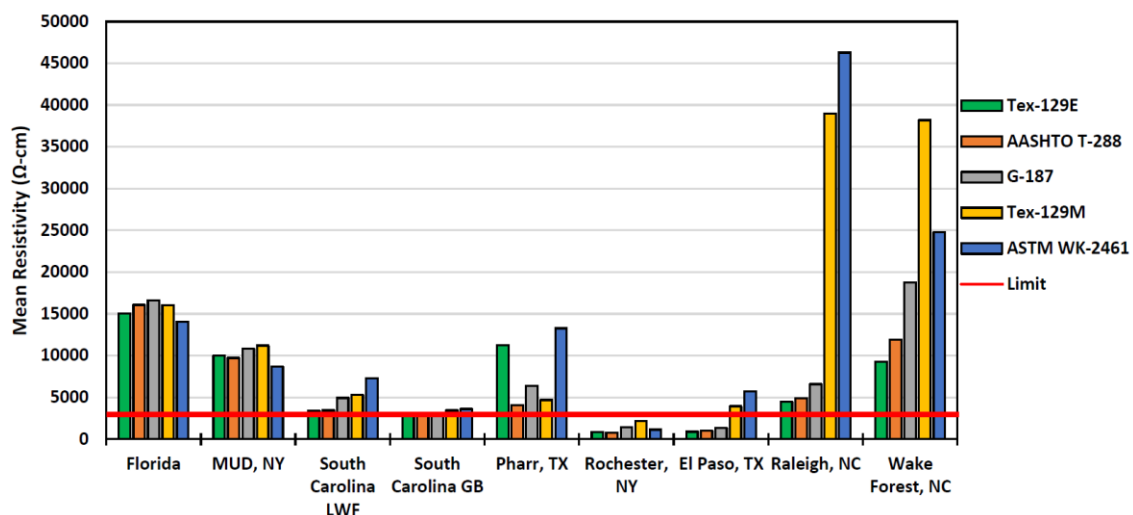


Figure 7. Resistivity Measured from NCHRP Project 21-11 [3].

5.8. Correlate sulfate and resistivity measurements

Salts influence the electrical resistivity of an aqueous solution because they dissociate into ions when dissolved in water, creating an electrically conductive solution. As the ion concentration increases, resistivity decreases due to higher ion mobility. Therefore, resistivity measurements are inversely correlated with salt content.

Figure 8 depicts the relationship between measurements of salt content (including sulfate) and resistivity. This relationship merges the data from NCHRP 21-11 related to normal weight aggregates with data from ESCS LWF collected by MTI and measurements of ESCS LWF from the project in Myrtle Beach SC and crushed ESCS from Louisiana

that we also included with the testing for NCHRP 21-11. Open circles are for the normal weight aggregates and the orange lines represent the typical relationship between sulfate content and resistivity for normal weight aggregates [1]. The solid squares and circles are from testing different sources of ESCS LWF. This figure shows that the higher sulfate contents reported from ESCS LWF correspond to higher resistivity compared to what would be expected for normal weight aggregates with similar sulfate contents. This is especially evident from the ESCS LWF samples with reported sulfate contents greater than 1400 ppm (LW2, LW4, LW5, and LW8).

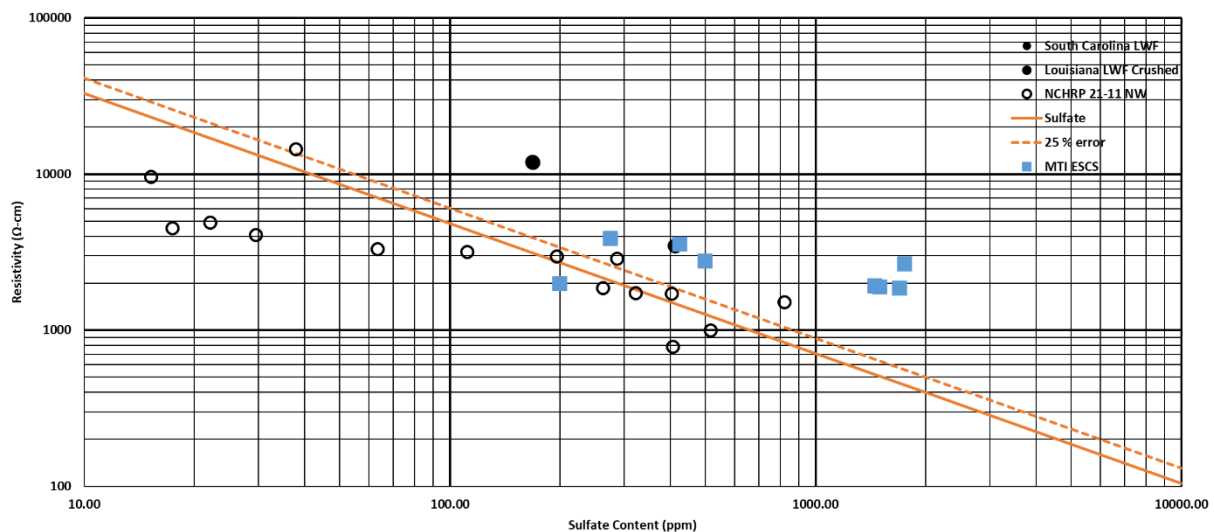


Figure 8. Trends Between Measurements of Salt Content and Resistivity from Test Procedures Selected Based on Coarseness of the Sample.

The ESCS data are included within the region outlined with the closed loop (maroon dot, SC LWF; yellow, Louisiana LWF crushed; and tan, Louisiana LWF uncrushed). These data show that the resistivity

of the LWF samples is high compared to the measurements made on samples of normal weight aggregates with similar salt contents.

6. Data from Resistivity and Corrosion Rate Measurements

Corrosion rate measurements are available from tests performed on samples of galvanized and plain steel specimens embedded within normal weight and ESCS aggregates. MTI performed measurements of corrosion rate from ESCS samples, and both normal weight and samples of LWF were included with the data collected as part of NCHRP 21-11. MTI performed corrosion rate measurements on laboratory specimens, and corrosion rate measurements reported for NCHRP 21-11 were field/in situ measurements. Both sets of measurements correspond to aggregates in the moist condition, which is the condition during service as

MSE wall fill is allowed to drain and will not become saturated during normal service conditions.

6.1. ESCS LWA – Resistivity vs CR

6.1.1. MTI – lab measurements

Figure 9 shows corrosion rates measured by MTI (2023) on specimens of ESCS after one month and three cycles of wetting and drying. Results of testing aqueous contents shows less resistivity for the same corrosivity. Wet conditions result in more corrosion and less resistivity than moist conditions. Corrosion rates measurements from the moist samples ranged between 1 $\mu\text{m}/\text{yr}$ and 25 $\mu\text{m}/\text{yr}$. These corrosion rates

are expected to attenuate with respect to time, and the highest observed corrosion rate of 25 $\mu\text{m}/\text{yr}$ is not higher than the expected corrosion rate for

galvanized steel with the first month of service and embedded in fills that meet AASHTO requirements for pH, salt content and resistivity.

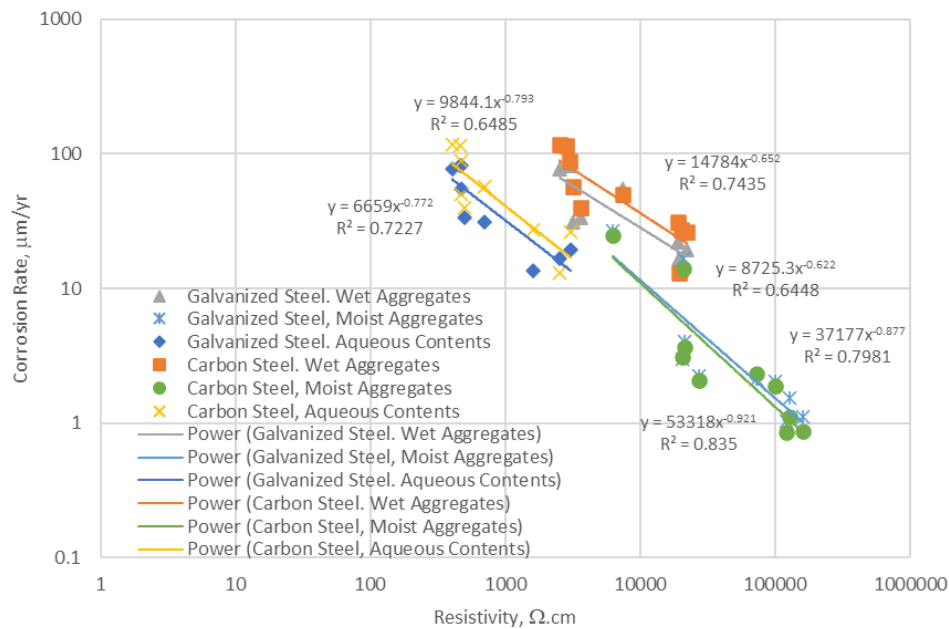


Figure 9. Variation of corrosion rates as a function of electrical resistivity [2].

The highest corrosion rates are observed from samples with the lowest resistivity and vice versa. Samples LW2 and LW5 (blended samples) had the highest measured corrosion rates of 27 $\mu\text{m}/\text{yr}$ and 17 $\mu\text{m}/\text{yr}$ and both of these samples had measured resistivity of 1852 $\Omega\cdot\text{cm}$ and 2646 $\Omega\cdot\text{cm}$ and sulfate content of 1700 ppm and 1750 ppm, respectively.

The corrosion rate for six out of eight samples is less than 4 $\mu\text{m}/\text{yr}$. The lowest corrosion rates are observed from Samples LW6 and LW7 with measured resistivity 30,385 $\Omega\cdot\text{cm}$ and 43,244 $\Omega\cdot\text{cm}$, and sulfate content < 500 ppm. These corrosion rates are less than corrosivity rate of NWCx that had significantly less sulfate content (**Figure 10**).

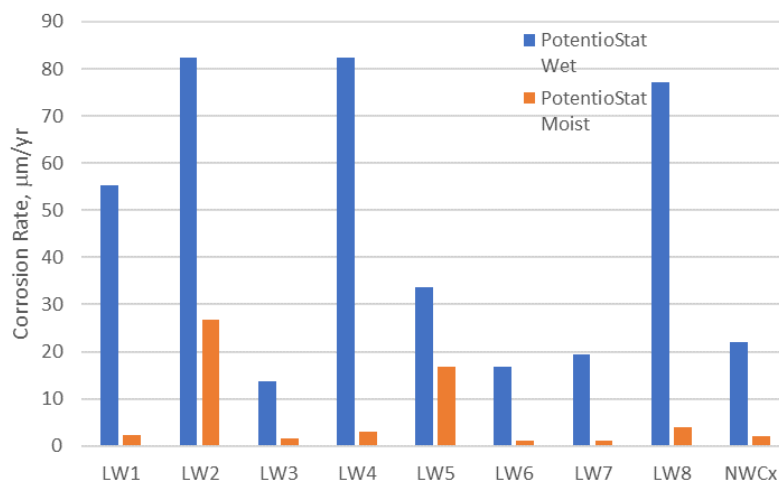


Figure 10. Corrosion Rate of Galvanized Steel Coupons During Wetting and Drying Cycles. (MTI 2023).

6.1.2. Myrtle Beach site – in situ field measurements

Laboratory tests and measurements of sulfate content and resistivity from samples of ESCS included with the NCHRP data and described as South Carolina LWF were performed on samples collected after construction of a viaduct along the US Route 17 bypass in Myrtle Beach, South Carolina. The US

Route 17 bypass is a four-lane, north-south, divided highway that crosses the east-west SC Route 707 and the Farrow Parkway in Myrtle Beach, South Carolina. Between the summer of 2012 and the winter of 2014, Horry County and the South Carolina Department of Transportation (SCDOT)

reconstructed this intersection to incorporate a viaduct that allowed US 17 to cross this intersection with a grade separation. Embankments for the north and south approaches are supported by mechanically stabilized earth retaining walls on the east and west sides. Two-stage construction of the mechanically stabilized earth (MSE) walls supporting the bridge approaches and lightweight expanded clay fill (LWF) were used to address the potential for settlements due to the soft foundation soils prevalent at the site.

The SCDOT and Horry County retained CDMSmith to study the performance (corrosion rates and metal loss) of galvanized steel reinforcements embedded within the MSE wall fills at this site over a two-year period and report their observations. CDMSmith subcontracted with McMahon & Mann Engineering

and Geology, P.C. (McMahon & Mann) to recommend and install a corrosion monitoring system at this site, and obtain measurements of site conditions, reinforcement conditions and corrosion rates. The following data are from the report of the study administered by CDMSmith and implemented by McMahon & Mann.

Figure 11 is a summary of corrosion rates (CR) measured from galvanized steel samples embedded in ESCS LWF in Myrtle Beach, SC between August 2016 and May 2019. These measurements indicate that the corrosion rates are less than 6.5 $\mu\text{m}/\text{yr}$ and attenuate with respect to time such that after two years the measured corrosion rates are less than 2 $\mu\text{m}/\text{yr}$.

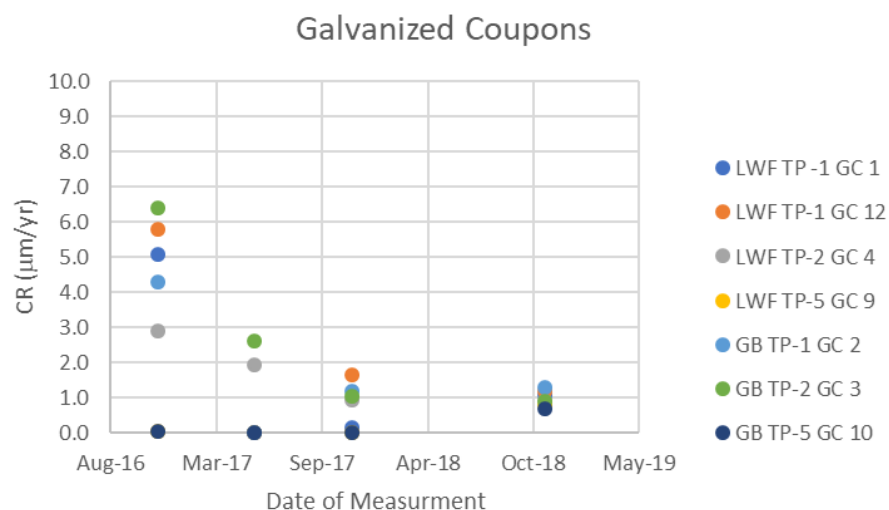


Figure 11. Field Measurements of Corrosion Rates vs. Time for Galvanized Steel Embedded in ESCS at Myrtle Beach, SC.

[Table 3](#) is a summary of the maximum, minimum and mean of the corrosion rates observed from the sample domain between November 2016 and November

2018. Data in [Table 3](#) include plain steel specimens showing that the corrosion rates observed for plain steel (i.e., not galvanized) are less than 3 $\mu\text{m}/\text{yr}$.

Table 3. Corrosion Rate Measurements from LWF in Myrtle Beach, SC.

SOUTH CAROLINA - LIGHT WEIGHT FILL					
Coupon	CR ($\mu\text{m}/\text{yr}$)	Nov-16	May-17	Nov-17	Nov-18
GC	MAX	5.8	1.9	1.7	1.3
	MIN	0.1	0.7	0.2	0.7
	MEAN	3.4	1.2	0.8	1.0
SC	MAX	1.3	1.5	2.1	15.3 ¹
	MIN	0.3	0.6	0.5	0.5
	MEAN	0.8	1.1	1.0	4.4 ¹
GC -galvanized steel coupons, SC- steel coupons					
¹ Outlier. Mean is 2.9 $\mu\text{m}/\text{yr}$ with outlier removed					

6.2. Normal weight aggregates – Resistivity vs. CR

Resistivity is an indicator of corrosivity, as it correlates with factors affecting corrosion, such as salt and moisture content [3]. Data, including corrosion rates and resistivity from sites across North America and Europe, are available from a database cataloged in NCHRP 24-28 [28]. The data set includes in situ corrosion rate measurements from the field, which involved variable moisture contents and locations near the tops and bases of MSE walls, using the linear polarization resistance technique. Generally, corrosion rates decrease over time as a protective scale develops on the steel surface, with most attenuation occurring within the first year. The corrosion rate measurements presented are from

samples embedded in fill for at least one year, indicating relatively stabilized rates [3].

Figure 12 merges the data from earlier studies related to normal weight aggregates (NCHRP, TAI and NBS studies) with data from ESCS LWF collected by MTI and measurements of ESCS LWF from the project in Myrtle Beach S.C. This figure shows that measurement of corrosion rate from samples of ESCS LWF are similar to those from normal weight fills at similar resistivity in spite of the higher sulfate contents reported for ESCS LWF. The two data points for MCI-ESCS that lie above 15 $\mu\text{m}/\text{yr}$ correspond to LW2 and LW5, which are the blended samples with finer particle sizes.

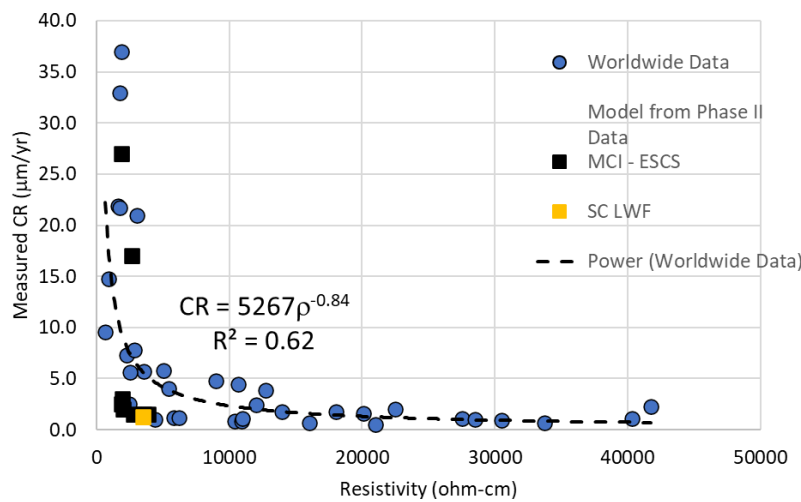


Figure 12. Galvanized steel corrosion rates and measurements of resistivity from worldwide data: Testing was done according to AASHTO T 288 on samples with more than 22% of particles passing the 2-mm (No. 10) sieve [3].

These data indicate that for normal weight aggregates with resistivity of 2000 $\Omega\text{-cm}$, a corrosion rate of 9 $\mu\text{m}/\text{yr}$ is expected and the range of corrosion rates observed with resistivity equal to 2000 $\Omega\text{-cm}$ is between 2.5 $\mu\text{m}/\text{yr}$ and 22 $\mu\text{m}/\text{yr}$.

Alternatively, corrosion rates can be related to indices which characterize corrosivity in terms of multiple variables that include parameters such as moisture content and the presence of carbonates and combines parameters to consider the interaction between pH, resistivity, salt content, moisture content and other site conditions to achieve a

corrosivity index. **Figure 13** shows the correlation between the corrosivity index described by Brady and McMahon (1994) [17] and corrosion rates observed from reinforcements included in the NCHRP Project 21-1. Using this scheme the LWF from South Carolina is characterized as non-aggressive relative to corrosion and together with the observed corrosion rate of 2 $\mu\text{m}/\text{yr}$ plots consistent with the trend line shown in **Figure 13**. This scheme may be useful for characterizing the corrosivity of ESCS consistent with normal weight fill.

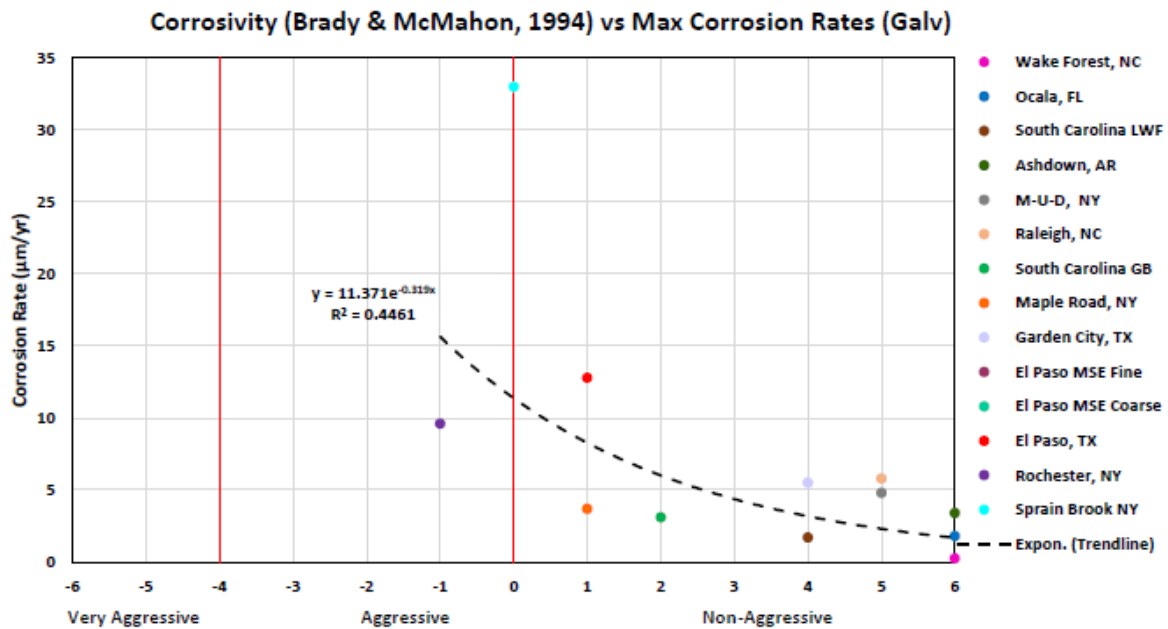


Figure 13. Corrosion Rates vs. Corrosivity Index [17].

7. Discussion of Results

7.1. ESCS LWA vs. NWA

For ESCS, high sulfate contents (>200 ppm) are observed from 13 out of 15 samples that were tested. Higher sulfate contents are observed from samples with a fine particle size gradation (quantify in terms of GN) compared to coarse samples.

The correlation between resistivity and sulfate content is different for ESCS compared to normal weight fill. Higher resistivity is observed for LWF samples compared to samples of normal weight fill with the same sulfate content.

Corrosion rates observed from samples of ESCS are similar to the corrosion rates observed from normal weight fills that do not have sulfate contents higher than 200 ppm. Corrosion rates measured in the lab with samples of ESCS with coarse gradations are less than 4 µm/yr, which is the metal loss rate considered in the design of MSE with galvanized steel reinforcements after 2-years in service as described by AASHTO for fills that meet AASHTO requirements for resistivity, salt content and pH. Corrosion rates for fine material tested in the lab by MTI are higher, between 17 µm/yr and 27 µm/yr, which are consistent with the AASHTO model that considers higher corrosion rates during the first two years of service, and in this case after 1 month. In situ measurements at Myrtle Beach depicting the performance of galvanized steel in ESCS suggest that

these corrosion rates will attenuate with respect to time.

Existing testing standards tend to measure the sulfate and chloride ion concentrations in unit weight of the materials, say mg/kg or ppm. However, these measurements neglect the low-density of the lightweight aggregates that yield less mass per unit volume of the placed backfills. Hence, the total concentration of corrosive ions is less than normal weight aggregates with the same weight-based concentration. This difference explains the difference between similar sulfate contents of LWA and NWA causing the same rate of corrosion.

7.2. Sulfate-Resistivity-Corrosion Correlations

Observations of sulfate contents taken over time show that decreasing sulfate contents are observed over time as a result of cycles of wetting and drying. This is due to the solubility of sulfate and how sulfate ions are mobilized as water infiltrates the fill. **Figure 14** shows how the measurements of sulfate content varied from samples of ESCS within the test boxes used for corrosion rate measurements during cycles of wetting and drying.

Figure 14 shows the temporal variation of sulfate contents measured by MTI over 3 cycles of wetting and drying. Changes in sulfate content are commensurate with higher resistivity and lower

corrosion rates. This supports the premise that corrosion rates attenuate with respect to time with fills that are allowed to drain.

Further to this point, [Table 4](#) shows measurements of sulfate content performed on samples of ESCS retrieved from test pits at the Myrtle Beach site. These test pits were advanced approximately 2 years

after the MSE walls were constructed and following events related to hurricane triggered flooding in the region. Initially, all samples of ESCS that were tested showed high sulfate contents in the range of 1370 ppm to 2589 ppm and resistivity between 1700 Ω -cm and 3216 Ω -cm.

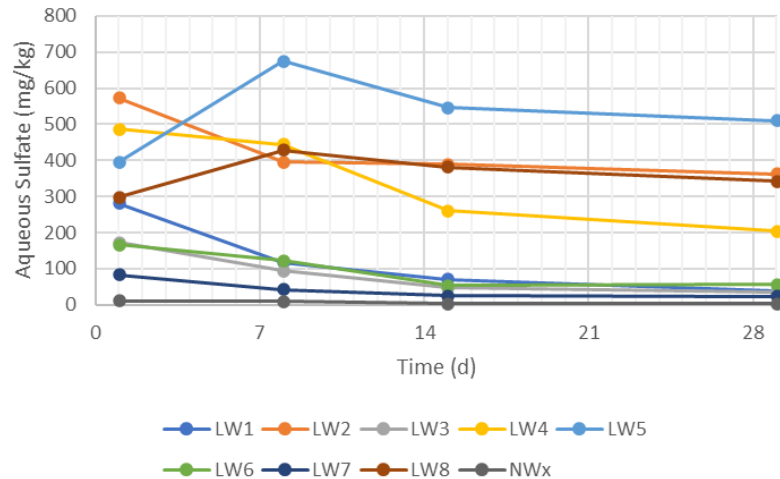


Figure 14. Sulfate contents during wetting and drying cycles [2].

The results from electrochemical testing presented [Table 4](#) show variations in measurements between the test pits. Two of the samples retrieved from TP-2 and TP-3 show higher levels of sulfates (1716 ppm

and 4325 ppm) and these are associated with relatively low resistivity, close to or less than 3000 Ω -cm.

Table 4. Test Results from LWF Sampled from Test Pits.

Location	Laboratory Measurements			
	pH	Resistivity (Ω -cm)	Cl ⁻ (ppm)	SO ₄ (ppm)
Test Pit #1 (11/16)	8.6	11,500	30	< 3
Test Pit # 2 (11/16)	6.8	3,150	35	1716
Test Pit # 3 (2016)	7.2	2,500	30	4325
Test Pit # 4 (11/16)	8.4	15,000	30	< 3
Test Pit # 5 (11/16)	7.8	10,500	< 30	< 3

However, not all samples from test pits show elevated levels of soluble sulfate and corresponding low resistivity. Sulfate contents measured from samples collected from TP-1, TP-4 and TP-5 are less than 3 ppm. Changes in electrochemical properties may be due to leaching of salts that occur as water

infiltrates and is discharged from the fill in cycles. TP-4 is located near a drainage inlet and both TP-1 and TP-5 are located directly behind the south and north bridge abutments. These are locations where water readily drains after infiltrating into the fill.

8. Conclusions

- Expanded slate, clay and shale are lightweight materials that differ from normal weight soils and aggregates in terms of its chemical composition and the porosity of individual particles.
- High sulfate contents have been observed from samples of light weight fill manufactured from expanded slate, clay and shale. High sulfate contents (> 200 ppm) have been observed from coarse and fine gradations.

3. Measurements of sulfate content are variable and depend upon the test method which differ in terms of sample treatments and measurement techniques.
4. Results from measurements of sulfate content on samples of ESCS and NWA can vary with respect to different labs. Labs may follow the same test standard but may employ different measurement techniques.
5. Test procedures that are typically followed by geotechnical engineering laboratories are developed from testing normal weight soils and aggregates and do not consider the characteristics particular to ESCS.
6. Sulfate contents are correlated with resistivity and the correlations differ with respect to normal weight soils and aggregates or ESCS. In general, for the same sulfate content, ESCS has a higher resistivity compared to normal weight materials.
7. If the sulfate content from ESCS are measured from leachate that has been drained from a sample after 24 hours of soaking, then the correlation between sulfate content and corrosivity are similar to that for normal weight materials. Sulfate contents measured from the leachate is less than the contents measured from the AASHTO standards.
8. ESCS is a free draining material that will not be saturated in service when used as MSE wall fill unless the wall becomes inundated. Therefore, the relevant measurement of corrosion rate is from the moist condition after samples have been subjected to cycles of wetting and drying. This is to simulate the effect of time on corrosion rates and the cycles of wetting and drying due to infiltration and subsequent drainage of stormwater.
9. After subjecting samples of ESCS to cycles of wetting and drying, decreased sulfate contents and increased resistivities are observed. Properties of ESCS may vary over time, and although these properties may not initially meet the project specifications they may converge to these limits within the first two years of service.
10. Corrosion rates attenuate with respect to cycles of wetting and drying/time.
11. Corrosion observed from galvanized steel reinforcements embedded within ESCS are generally equal to or less than those observed from normal weight material with sulfate content < 200 ppm.
12. Corrosion rates measured from samples of ESCS are not well correlated with sulfate content, but the correlation with respect to the measurements of resistivity is better.
13. Observed field performance indicates that corrosion rates used in design are applicable and the reinforcement cross sections are expected to provide rupture resistance with an adequate factor of safety throughout the intended service life of the wall.
14. The low density of ESCS LWA yields to less mass of materials and hence, sulfate measures should be based on the unit volume of the backfill and reduced in-place density for comparison purposes.

9. Recommendations

9.1. Testing Standards (sample preparation and measurement techniques)

Develop modified test procedures that are applicable to ESCS and coarse NWA considering actual gradation, compaction, and moisture content. We recommend that these modified test procedures would be from AASHTO T 290 for gradations that include more than 20% passing a #10 sieve and Tex-620-M for coarse aggregates (< 20% passing the #10 sieve).

The sulfate contents for ESCS need to be evaluated considering the light weight of the fill. If the sulfate content is expressed in terms of parts per million with respect to the weight of the solids (mg/kg), then the threshold for ESCS LWF should be adjusted to be equivalent to the threshold that applies to normal weight aggregates. The threshold for ESCS should be

such that the resistivity is similar to the threshold for normal weight aggregates (i.e., what sulfate content renders a resistivity when saturated of 3000 Ω -cm). Another approach would be to assess the corrosivity of the ESCS on the basis of resistivity measurements, without including measurements of sulfate content. Alternatively sulfate content could be expressed on a volumetric, rather than a gravimetric, basis to achieve a value that is equivalent to values obtained with normal weight aggregates.

Due to the absorption inherent to ESCS, intraparticle moisture may include sulfate, but these ions are not included within the electrolyte that surrounds the buried metals. Therefore, this portion of the sulfate content does not affect the interparticle resistivity

which includes the two-phase solid liquid surrounding and in direct contact with the embedded steel, and which affects the corrosivity and performance of the steel. The effect of intraparticle moisture and sulfate content on the conductivity and corrosivity of interparticle moisture and sulfate should be investigated and relevant modifications to existing test procedures implemented to mitigate the effects that the intraparticle conditions have on the test results and characterization of corrosivity.

One modification may involve first testing for sulfate content after achieving a saturated surface dry condition of the aggregates, followed by testing a completely saturated sample. Moisture to be extracted from the SSD condition would need to be obtained by centrifuging the sample. In this manner the sulfate content from intraparticle moisture can be distinguished from sulfate that is contained on the surfaces of the particles (interparticle sulfate content).

Alternatively, samples may be tested after soaking for 72 hours such that the samples' intra- and interparticle pore spaces are filled with water. The solution extracted for testing sulfates would be decanted without centrifuging to procure only the leachate that is easily drained from surrounding the particles and none or very little from within the particles.

Possible sources of interference that may be inherent to ESCS and affect different measurement techniques such as spectrophotometry, gravimetric measurements or ion exchange chromatography need to be identified. For example, turbidity measurements obtained via spectrophotometry are affected by insoluble suspended matter and gravimetric measurements may be affected by the presence of sulfites and sulfides. Whether or not these substances are present within the makeup of samples prepared from ESCS needs to be investigated, and the effects that these species or conditions have upon the measurements needs to be mitigated.

9.2. Construction Specifications (acceptable limits)

Current specifications for selection of ESCS as backfill materials should be updated. One approach is to rely more on the measurements of resistivity for characterizing corrosivity of ESCS and not rely on measurements of sulfate content. Alternatively, the

allowable sulfate content could be modified to be more consistent with observations of performance and not limited to 200 ppm. It is essential to consider the low density of ESCS aggregates that result in a reduction in the mass of materials per given volume of backfills compared with normal weight aggregates. A realistic measure of ion concentration per volume can be obtained using the in-place density of ESCS aggregates.

Current practice is to apply the AASHTO criteria for the electrochemical properties of fill, which is a univariate approach. If one of the measured quantities including pH, resistivity, sulfate and chloride ion contents is outside of the given range or limit, the material is not considered suitable as fill for MSE wall construction. A multivariate scheme, such as the scheme described by Bady and McMahon (1984) should be implemented that considers the synergy between these parameters and other site conditions including drainage and the presence of ions that may form a protective scale and be favorable for corrosivity.

9.3. Future Studies and Testing of ESCS

The following topics would improve our understanding of the interaction of ESCS with moisture and its effects on corrosivity:

1. Evaluate the effect of modified test procedures on the measurements of sulfate content for ESCS.
2. Evaluate alternatives for expressing sulfate content for ESCS on a gravimetric as well as a volumetric basis.
3. Evaluate the relationships between characterization of corrosivity and performance of embedded metals for ESCS.
4. Conduct further studies to understand the physio-chemical properties of ESCS interacting with the moisture dynamics and its effect in electrochemical properties measurement.
5. Obtain data from ESCS placed in the field including electrochemical properties and how these may be affected by time, measurements of metal loss and corrosion rates of metals embedded with ESCS and correlating these data with data from production plants and laboratory studies.

FUNDING/SUPPORT

Not mentioned any Funding/Support by authors.

ACKNOWLEDGMENT

This paper is a reprint of a white paper. The paper utilizes data from NCHRP Research Report 21-11, "Electrochemical Test Methods to Evaluate the Corrosion Potential of Earthen Materials," (2021) and CA MTI Research Report 23-11, "Extending the Service-Life of Bridges Using Sustainable and Resilient Abutment Systems: An Experimental Approach to the Electrochemical Characterization of Lightweight Mechanically Stabilized Earth," (2023) to assess current practices and recommend practical specifications.

AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the authorship and/or publication of this paper.

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